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Mobile WiMAX MIMO Performance Analysis: Downlink and Uplink

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Abstract—Demand for broadband services continues to grow. Conventional high-speed broadband solutions are based on wired-access technologies, such as digital subscriber line (DSL). This type of solution is difficult to deploy in remote areas, and furthermore it lacks support for terminal mobility. Broadband Wireless Access (BWA) offers a flexible and cost-effective solution to these problems. The WiMAX standard has emerged to harmonize the wide variety of different BWA technologies. The most recent WiMAX standard (802.16e) supports broadband applications to mobile terminals and laptops. This paper analyses the performance of a mobile WiMAX system operating in an urban microcell. As an extension to the basic SISO mode, a number of 2x2 MIMO extensions are analysed. Simulated packet error rate and throughput results are presented for each link-speed. The paper highlights the trade-off between peak error-free throughput and robust operation at low SNR.

Keywords—IEEE 802.16e, BWA, Mobile WiMAX, MIMO

I. INTRODUCTION

The first WiMAX systems were based on the IEEE 802.16-2004 standard [1]. This targeted fixed broadband wireless applications via the installation of Customer Premises Equipment (CPE). In December, 2005 the IEEE completed the 802.16e-2005 [2] amendment, which added new features to support mobile applications. The resulting standard is commonly referred to as mobile WiMAX.

Mobile WiMAX integrates a rich set of features that offer considerable flexibility in terms of deployment options, as well as potential applications. The original WiMAX physical layer (PHY) used orthogonal frequency division multiplexing (OFDM). This provides strong performance in multipath and non-line-of-sight (NLOS) environments.

Mobile WiMAX extends the OFDM PHY layer to support efficient multiple-access. The resulting technology is known as scalable OFDMA. Data streams to and from individual users are multiplexed to groups of subchannels on the downlink and uplink. By adopting a scalable PHY architecture, mobile WiMAX is able to support a wide range of bandwidths. The scalability is implemented by varying the FFT size from 128 to 512, 1024, and 2048 to support channel bandwidths of 1.25 MHz, 5 MHz, 10 MHz, and 20 MHz respectively. This differs from the 802.11a/g standard (more commonly known as WiFi), where no multiplexing of users is performed at the OFDM symbol level. Since system bandwidth is limited and user demand continues to grow, spectral efficiency is vital. One way to improve link capacity, and potentially increase spectral

efficiency, is the application of MIMO. Mobile WiMAX supports a full-range of smart antenna techniques, including beamforming, spatial transmit diversity and spatial multiplexing (SM). Beamforming, or more specifically eigen-beamforming, requires Channel State Information (CSI) at the transmitter [3]. Spatial transmit diversity is achieved by applying Alamouti's Space-Time coding on the Downlink (DL) [4], and Space-Frequency Coding on the Uplink (UL) [5]. SM can also be employed on the DL and UL to increase the error-free peak throughput [6]. Finally, collaborative SM can be used on the UL, where multiple users with a single antenna transmit collaboratively in the same slot to a common multi-element basestation.

This paper investigates the performance of the mobile WiMAX standard when MIMO techniques are applied. Packet Error Rate (PER) and throughput results are presented for a MIMO-enabled UL and DL. Results are compared with basic SISO operation.

II. MOBILE WiMAX PHY DESCRIPTION

The mobile WiMAX standard builds on the principles of OFDM by adopting a Scalable OFDMA-based PHY layer (SOFDMA). SOFDMA supports a wide range of operating bandwidths to flexibly address the need for various spectrum allocation and application requirements. When the operating bandwidth increases, the FFT size is also increased to maintain a fixed subcarrier frequency spacing of 10.94 kHz. This ensures a fixed OFDMA symbol duration. Since the basic resource unit (i.e. the OFDMA symbol duration) is fixed, the impact of bandwidth scaling is minimized to the upper layers.

Table I shows the relevant parameters for the mobile WiMAX OFDMA PHY.

TABLE I. OFDMA PHY PARAMETERS

Parameter	Value			
FFT size	128	512	1024	2048
Channel bandwidth (MHz)	1.25	5	10	20
Subcarrier frequency spacing (kHz)	10.94			
Useful symbol period (μs)	91.4			
Guard Time	1/32, 1/16, 1/8, 1/4			

Table II summarises the OFDMA parameters used in our evaluation of the Mobile WiMAX standard.

TABLE II. OFDMA PARAMETERS

Parameter	Value	
Channel bandwidth (MHz)	5	
Sampling frequency F_s (MHz)	5.6	
Sampling period $1/F_s$ (μs)	0.18	
Subcarrier frequency spacing $\Delta f = F_s/N_{FFT}$ (kHz)	10.94	
Useful symbol period $T_b = 1/\Delta f$ (μs)	91.4	
Guard Time $T_g = T_b/8$ (μs)	11.4	
OFDMA symbol duration $T_s = T_b + T_g$ (μs)	102.9	
	DL PUSC	UL PUSC
Number of used subcarriers (N_{used})	421	409
Number of pilot subcarriers	60	136
Number of data subcarriers	360	272
Number of data subcarriers/subchannel	24	16
Number of subchannels	15	17
Number of users (N_{users})	3	3
Number of subchannels/user	5	4

Fig. 1 shows the block diagram of the MIMO enabled WiMAX simulator used in this paper.

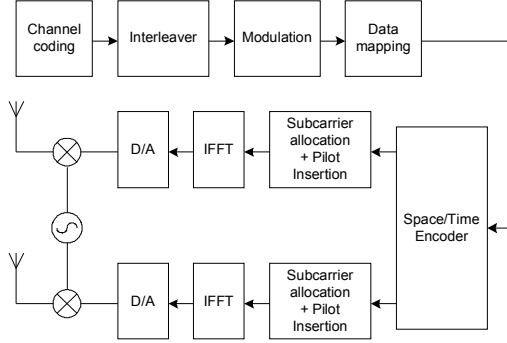


Figure 1. Mobile WiMAX functional stages

A. Channel coding

The channel coding stage includes randomization, coding and puncturing. Initially the input data is randomized in order to avoid long runs of ones and zeros. The output of the data randomizer is encoded with a convolutional encoder whose constraint length is 7, and the native code rate is 1/2. The puncturing block punctures the output of the convolutional encoder to produce higher code rates.

B. Interleaving

The interleaving stage uses a block interleaver to interleave the encoded bits. This maps adjacent encoded bits onto separated subcarriers, thus minimizing the impact of burst errors caused by spectral nulls (interestingly, such interleaving is not present in the 802.11a/g standard).

C. Modulation

The modulation block converts a sequence of interleaved bits into a sequence of complex symbols depending on the chosen modulation scheme (QPSK, 16QAM, and 64QAM).

D. Data mapping

In order to understand the operation of the data mapping block, it is necessary to explain a number of specific OFDMA terms.

Slot: This is the minimum possible data allocation unit in the OFDMA PHY. For DL PUSC, one slot represents one subchannel over two OFDMA symbols. For UL PUSC, one slot represents one subchannel over three OFDMA symbols

Data region (or data burst): a data region of a user is a two-dimensional allocation of a group of contiguous logical subchannels (which will later be physically distributed when the distributed permutation is chosen), in a group of contiguous slots. The size of the data region will depend on the number of subchannels allocated to each user and the user packet size. Values of 4 (UL) and 5 (DL) are used for the allocated subchannels, and a user packet size of 120 bytes is assumed.

The first step in the data mapping process is to segment the sequence of modulation symbols into a sequence of slots. Each slot contains a number of modulation symbols. For example, in DL PUSC each slot contains 48 symbols.

The second step is to map the slots into a data region, so that the lowest numbered slot occupies the lowest numbered subchannel among the allocated subchannels. The mapping of slots continues vertically to the edge of the data region, and then moves to the next available OFDMA slot [2]

E. Space/Time Encoder (MIMO encoder)

The Space/Time Encoder stage converts one single input data stream into multiple output data streams. How the output streams are formatted depends on the type of MIMO method employed.

F. Subcarrier allocation/Pilot insertion

At this stage all data symbols are mapped to a data region and assigned to their corresponding logical subcarriers. The next step is to allocate the logical subcarriers to physical subcarriers using a specific subcarrier permutation; pilots are also inserted at this point.

G. IFFT and Digital-to-Analog (D/A)

The final stage is to convert the data into analogue form (in the time-domain) for use in the radio front end. A guard interval is also inserted at this stage.

Our simulation supports a number of link-speeds (see Table III for details). A link-speed is defined as a combination of a modulation scheme and a coding rate. The peak data rate D is calculated as below:

$$D = N_D N_b R_{FEC} R_{STC} / T_s$$

where N_D , N_b , R_{FEC} , R_{STC} , and T_s denote the number of assigned data subcarriers to each user, the bits per sub-carrier, the FEC coding rate, the space-time coding rate, and the OFDMA symbol duration respectively. On the UL, more subchannels are used for control purposes, and more pilots are assigned to a subchannel. Hence, compared to the DL, less data subcarriers are available on the UL (see Table II).

TABLE III. MIMO MOBILE WiMAX LINK SPEEDS

Mode (Link-Speed)	No. of coded bits per subchannel DL/UL	No. of data bits per subchannel DL/UL	STBC 2x2 DL/UL bit rate/user (Mbps)	SM 2x2 DL/UL bit rate/user (Mbps)
QPSK 1/2	48/32	24/16	1.17/0.62	2.34/1.24
QPSK 3/4	48/32	36/24	1.75/0.93	3.5/1.86
16 QAM 1/2	96/64	48/32	2.33/1.24	4.66/2.49
16 QAM 3/4	96/64	72/48	3.50/1.87	7/3.73
64 QAM 1/2	144/96	72/48	3.50/1.87	7/3.73
64 QAM 2/3	144/96	96/64	4.66/2.49	9.33/4.98
64 QAM 3/4	144/96	108/72	5.25/2.80	10.50/5.60

III. MIMO WIDEBAND CHANNEL MODEL

The channel model used in our simulation is based on the spatial channel model (SCM) [7]. This model was developed by ETSI 3GPP-3GPP2 to help standardise the outdoor evaluation of SISO and MIMO mobile systems. The 3GPP SCM defines three typical cellular environments, namely urban macrocell, suburban macrocell, and urban microcell,

Based on the above 3GPP-SCM channel model, an urban micro 3GPP tapped delay line (TDL) channel model is generated for use in our analysis. The TDL comprises 6 taps with non-uniform delays. The MS velocity is assumed to be 40 km/h. The antenna element separation is half a wavelength. The resulting spatial correlation coefficient is 0.16, which represents a highly uncorrelated set of spatial channel. The channel has the following parameters:

TABLE IV. 3GPP TDL CHANNEL PARAMETERS

	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
Delay (ns)	0	210	470	760	845	910
Power (dB)	0	-1.8	-1.5	-7.2	-10	-13
K factor	0	0	0	0	0	0
Delay spread	279 ns					

IV. MIMO SCENARIOS DESCRIPTION

A. Space-Time Block Coding (STBC) Downlink

Our mobile WiMAX simulator implements the Alamouti scheme [4] on the DL to provide transmit and receive diversity. This scheme uses a transmission matrix $\begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}$, where s_1 and s_2 represents two consecutive OFDMA symbols.

B. Space-Frequency Block Coding (SFBC) Uplink

The mobile WiMAX system implements spatial transmit diversity differently on the DL and UL. While the DL applies Alamouti's STBC; the UL deploys an Alamouti-based SFBC [2]. The motivation behind the use of SFBC comes from the fact that STBC requires the channel to remain stationary over two consecutive OFDMA symbols. In a fast-fading radio channel, this condition may not always be satisfied. To overcome this problem, SFBC is introduced. In this method the coding is implemented across two consecutive subcarriers in the frequency domain, and thus within the OFDMA symbol. This eliminates the need for channel stationary over a pair of

OFDMA symbols. The mapping scheme is designed in such a way that on the first antenna the symbol stream can be sent without modification; hence the SFBC system can work as a SISO system if the second antenna is switched off. Fig. 2 illustrates the block diagram for SFBC.

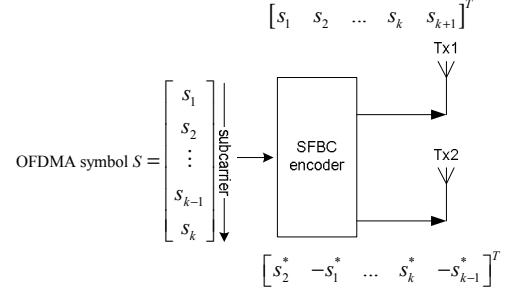


Figure 2. SFBC Transmit Block Diagram

SFBC works on the assumption that two adjacent subcarriers in the frequency domain experience correlated fading. This assumption holds in channels where the delay spread is low enough for the resulting coherence bandwidth to exceed twice the subchannel spacing. This criterion is also the reason why SFBC cannot be used on the DL. On the DL all the OFDMA subcarriers allocated to a given user are physically distributed, meaning the above assumption cannot be satisfied. On the UL the allocated subcarriers to a given user follow multiple sets of four adjacent subcarriers.

C. Spatial Multiplexing (SM)

Mobile WiMAX supports SM [6] to increase the peak error-free data rate by transmitting separate data streams from each antenna. A 2x2 SM system can double the peak data rate. This comes at the expense of sacrificing diversity gain, and hence a much higher SNR is required.

V. SIMULATION PERFORMANCE ANALYSIS

In this section SISO and MIMO PER and throughput results are presented using the Mobile WiMAX simulator and channel model described in sections II, III and IV. On the DL a 3-sector BS is assumed. This transmits data simultaneously to 3 MS, with each sharing a common OFDMA symbol. On the UL, the same 3 MS transmit their data to the BS using another shared OFDMA symbol. Perfect channel estimation and synchronisation is assumed. For those modes based on SM, an MMSE receiver is used to remove the inter-stream interference on a per sub-carrier basis.

The link throughput for each user is calculated from the PER as follows: $R = D(1 - \text{PER})$, where D represents the peak transmission rate calculated in section II.

A. MIMO DL WiMAX analysis

Fig. 3 compares the PER performance for the SISO and STBC DL; both 2x1 and 2x2 STBC systems are considered. It can be seen that the PER performance is enhanced by 2x1 and 2x2 STBC. More specifically, at a PER of 10^{-2} , for 1/2 rate 16QAM the improvement is 3dB and 9dB respectively for 2x1 and 2x2 STBC.

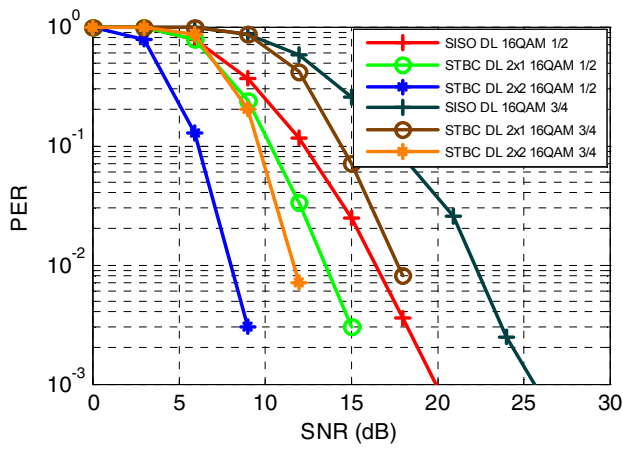


Figure 3. PER SISO vs STBC comparison

Fig. 4 and Fig. 5 present the throughput versus SNR graphs for the DL SISO and STBC 2x2 scenarios. We observe that STBC offers a significant performance gain of 3–9dB, the exact value depend on the selected link-speed. As expected, STBC does not improve the peak error-free data throughput, however at a given SNR STBC (when combined with suitable link adaptation) can provide a significant increase in throughput (since higher throughput modes can be used at much lower values of SNR).

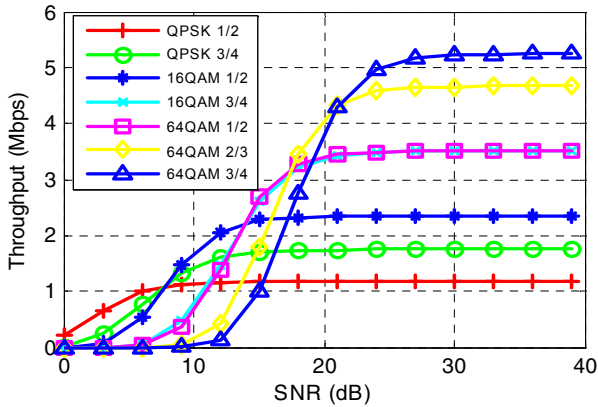


Figure 4. SISO DL Throughput

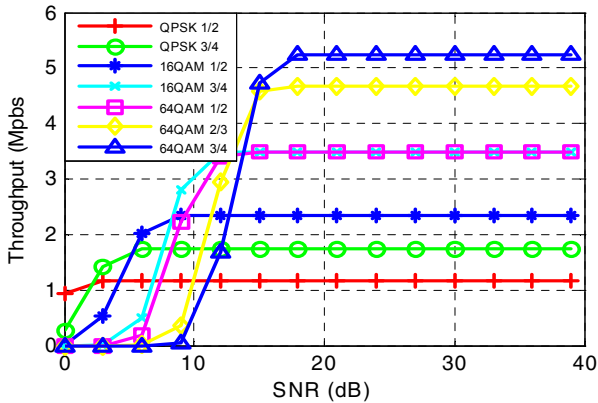


Figure 5. STBC 2x2 DL Throughput

The simulated DL throughput with SM 2x2 is illustrated in Fig. 6. As expected, the SM 2x2 mode doubles the peak error-free throughput of every link-speed. However, at low SNR values the throughput of SM is less than STBC.

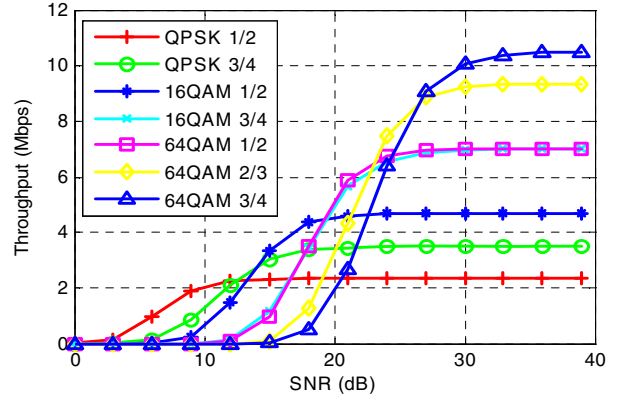


Figure 6. SM 2x2 DL Throughput

Fig. 7 shows the throughput envelope versus SNR for all the investigated mobile DL WiMAX scenarios: SISO, STBC 2x2, and SM 2x2. This envelope assumes the use of adaptive modulation and coding (AMC) to maximise the expected throughput. Obviously, both MIMO schemes outperform the SISO scenario. However, for a very spatially correlated channel, the SM method can be worse than SISO. In this case STBC performance would tend to that of SISO. The STBC DL produces the best performance at low to medium values of SNR, due to its robustness in poor channel conditions. On the other hand, at high SNR the increased error-free data rate makes SM the best choice. Mobile WiMAX supports Adaptive MIMO Switching (AMS) to select the best MIMO scheme. Fig. 7 clearly shows that for the channel conditions analysed here, the switching point between STBC and SM is 20dB. This value will increase with increasing spatial correlation.

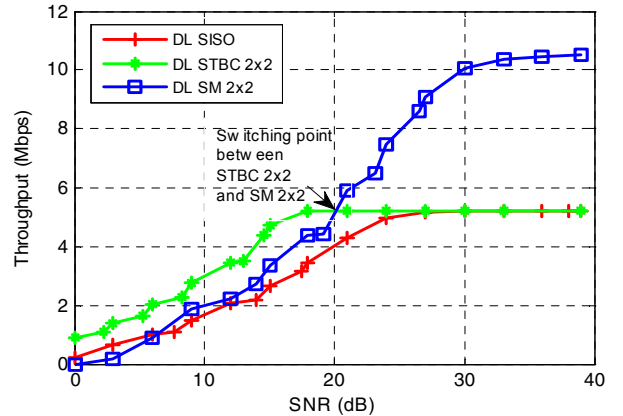


Figure 7. Switching point between DL STBC 2x2 and DL SM 2x2

B. MIMO UL WiMAX

The UL PER performance for SISO and SFBC is shown in Fig. 8. A substantial improvement in the PER performance can be seen over the SISO case. For a PER of 10^{-2} , the improvement for 1/2 rate 16QAM is 4dB and 9dB respectively for 2x1 and 2x2 SFBC.

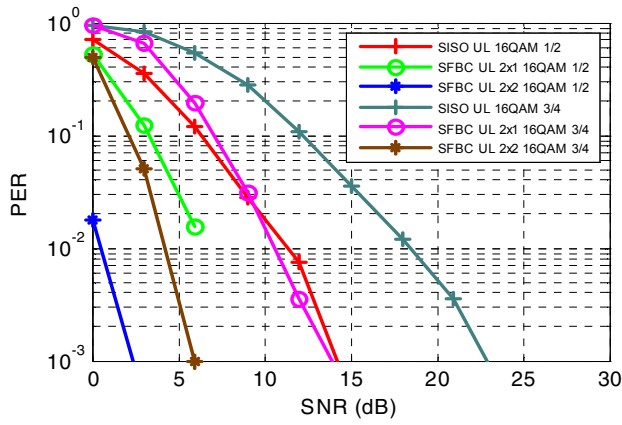


Figure 8. PER SISO vs SFBC comparison

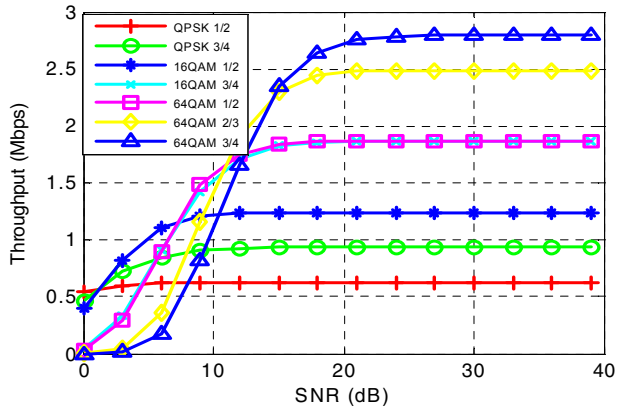


Figure 9. SISO UL Throughput

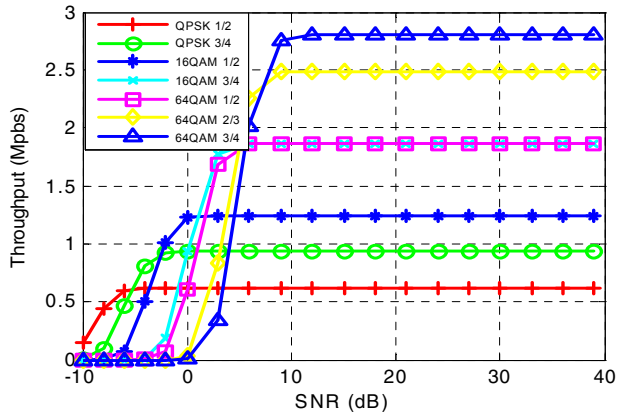


Figure 10. SFBC 2x2 UL Throughput

Fig. 9 and Fig. 10 present the throughput versus SNR results for the UL SISO and SFBC 2x2 modes. Compared to the DL, we see that the UL SISO and SFBC schemes both achieve their peak throughput at a reduced value of SNR (7.5dB in this case). This gain is known as the sub-channelization gain. It occurs since the transmit power is spread over a smaller subset of subcarriers on the UL.

Fig. 11 shows the throughput envelope versus SNR for all the investigated mobile UL WiMAX scenarios: SISO, SFBC

2x2 and SM 2x2. We observe a SFBC/SM switching point of 16 dB (i.e. 4dB less than the DL).

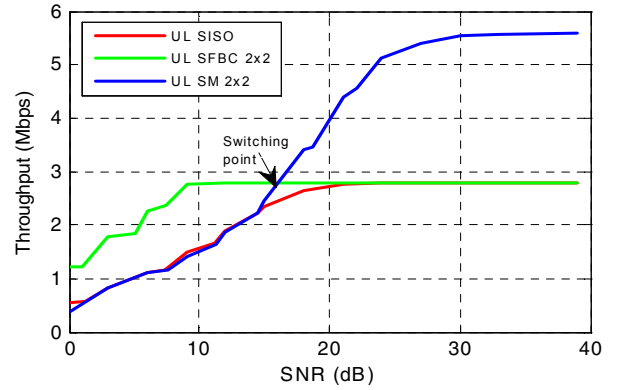


Figure 11. Switching point between UL SFBC 2x2 and UL SM 2x2

VI. CONCLUSIONS

This paper has presented a detailed study of the throughput benefits of MIMO when applied to mobile WiMAX. The matrix channel was modelled using the well-known 3GPP spatial channel model. The simulation is fully compliant to the 802.16e-2006 standard. Throughput results were presented for both the DL and UL. In both cases, at lower values of SNR STBC (DL) and STFC (UL) are preferred. However, at high SNR AMS should be used to switch to SM. Given that SM 2x2 doubles the error-free throughput, at high SNR this scheme leads to the highest throughput. In practice, the viability of SM (and the value of the SNR switching threshold) depends on the level of spatial correlation.

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